

# Forward Physics in Proton-Nucleus and Nucleus-Nucleus Collisions

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**Abstract.** We present an universal treatment for a substantial nuclear suppression representing a common feature of all known reactions on nuclear targets (forward production of high- $p_T$  hadrons, production of direct photons, the Drell-Yan process, heavy flavor production, etc.). Such a suppression at large Feynman  $x_F$ , corresponding to region of minimal light-cone momentum fraction variable  $x_2$  in nuclei, is tempting to interpret as a manifestation of coherence or the Color Glass Condensate. We demonstrate, however, that it is actually a simple consequence of energy conservation and takes place even at low energies, where no effects of coherence are possible. We analyze this common suppression mechanism for several processes performing model predictions in the light-cone dipole approach. Our calculations agree with the data.

**Keywords:** nuclear suppression, Feynman  $x_F$  scaling, large rapidity gap, Color Glass Condensate

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## INTRODUCTION

In the proton(deuteron)-nucleus and nucleus-nucleus collisions, investigated at the Relativistic Heavy Ion Collider (RHIC), recent measurements of high- $p_T$  particle spectra by the BRAHMS [1, 2], STAR [3] and PHENIX [4] Collaborations show a strong nuclear suppression. Observed nuclear effects occur not only at large forward rapidities [1, 2, 3] but unexpectedly also at midrapidities [4].

Besides, quite strong and universal nuclear suppression at large Feynman  $x_F$  is confirmed by the collection of data from [5] for the production of different species of particles in  $p - A$  collisions. The rise of the nuclear suppression with  $x_F$  is also supported by the NA49 data [6] at lower energy corresponding to c.m.s. energy  $\sqrt{s} = 17.3 \text{ GeV}$ . The onset of strong nuclear effects at large  $p_T$  has been also demonstrated for direct photon production in  $Au - Au$  collisions at RHIC by the PHENIX Collaboration [7]. The E772 experiment at Fermilab [8] first observed that the Drell-Yan (DY) process is considerably suppressed at large  $x_F$ .

Assuming large forward rapidities, the basic explanation for such an effect has been based on an idea that in this kinematic region corresponding to the beam fragmentation region at large Feynman  $x_F$  one can reach the smallest values of the light-front momentum fraction variable  $x_2$  in nuclei. It allows to access the strongest coherence effects such as those associated with shadowing or the Color Glass Condensate (CGC).

It was shown in refs. [9, 10, 11] that a considerable nuclear suppression for any reaction at large  $x_F$  (small  $x_2$ ) is caused by another effects, which can be easily misinterpreted

as coherence. Such a suppression can be treated, alternatively, as a Sudakov suppression, a consequence of a reduced survival probability for large rapidity gap (LRG) processes in nuclei, an enhanced resolution of higher Fock states by nuclei, or an effective energy loss that rises linearly with energy. It was demonstrated in refs. [9, 10] that the nuclear suppression at large  $x_F$  is a leading twist effect, violating QCD factorization.

In this paper we will analyze nuclear suppression at large rapidities (large  $x_F$ ) for the following processes occurring in  $p(d) - A$  and  $A - A$  collisions:

- production of leading hadrons with small  $p_T$
- high- $p_T$  hadron production at forward rapidities in  $p(d)-A$  collisions
- production of hadrons at small energies vs. NA49 data
- high- $p_T$  hadron production at midrapidities
- direct photon production in Au-Au collisions
- Drell-Yan production at large  $x_F$

## SURVIVAL PROBABILITY OF LARGE RAPIDITY GAPS

Treating any hard reaction, which is LRG process in the limit  $x_F \rightarrow 1$ , gluon radiation is forbidden by energy conservation. If a large- $x_F$  particle is produced, the rapidity interval to be kept empty is  $\Delta y = -\ln(1 - x_F)$ . Assuming as usual an uncorrelated Poisson distribution for gluons, the Sudakov suppression factor, i.e. the probability to have a rapidity gap  $\Delta y$ , becomes

$$S(\Delta y) = e^{-\langle n_G(\Delta y) \rangle}, \quad (1)$$

where  $n_G(\Delta y)$  is the mean number of gluons that would be radiated within  $\Delta y$  if energy conservation were not an issue.

The mean number  $\langle n_G(\Delta y) \rangle$  of gluons radiated in the rapidity interval  $\Delta y$  is related to the height of the plateau in the gluon spectrum,  $\langle n_G(\Delta y) \rangle = \Delta y dn_G/dy$ . Then, the Sudakov factor acquires the simple form,

$$S(x_F) = (1 - x_F)^{dn_G/dy}. \quad (2)$$

The height of the gluon plateau was estimated in ref. [12] as,

$$\frac{dn_G}{dy} = \frac{3\alpha_s}{\pi} \ln \left( \frac{m_\rho^2}{\Lambda_{QCD}^2} \right). \quad (3)$$

For further calculations we take  $\alpha_s = 0.4$  (see discussion in ref. [9]), which gives with high accuracy  $dn_G/dy = 1$ , i.e. the Sudakov factor,

$$S(x_F) = 1 - x_F. \quad (4)$$

One can formulate nuclear suppression as  $x_F \rightarrow 1$  as a survival probability of the LRG in multiple interactions with the nucleus. Every additional inelastic interaction contributes an extra suppression factor  $S(x_F)$ . The probability of an  $n$ -fold inelastic collision is related to the Glauber model coefficients via the Abramovsky-Gribov-Kancheli

(AGK) cutting rules [13]. Then the survival probability at impact parameter  $\vec{b}$  reads,

$$W_{LRG}^{hA}(b) = \exp[-\sigma_{in}^{hN} T_A(b)] \sum_{n=1}^A \frac{1}{n!} \left[ \sigma_{in}^{hN} T_A(b) \right]^n S(x_F)^{n-1}, \quad (5)$$

where  $T_A(b)$  is the nuclear thickness function.

## PRODUCTION OF LEADING HADRONS WITH SMALL $p_T$

The left panel of Fig. 1 shows the collection of data from [5] for production of different species of particles in  $p - A$  collisions exhibiting quite a strong and universal suppression at large  $x_F$ . Moreover, these data cover the laboratory energy range from 70 to 400 GeV and demonstrate so the  $x_F$  scaling of nuclear effects.

It is natural to relate the observed suppression to the dynamics discussed in the previous section. The nuclear effects can be calculated using Eq. (5) summing over the number of collisions and integrating over the impact parameter,

$$R_{A/N}(x_F) = \frac{1}{(1-x_F) \sigma_{eff} A} \int d^2 b e^{-\sigma_{eff} T_A(b)} \left\{ e^{(1-x_F) \sigma_{eff} T_A(b)} - 1 \right\}. \quad (6)$$

In the Glauber model  $\sigma_{eff} = \sigma_{in}^{NN}$ . However, Gribov's inelastic shadowing corrections substantially reduce  $\sigma_{eff}$  [14, 15].

To compare with data, the nuclear effects are parametrized as  $R_{A/N} \propto A^\alpha$ , where the exponent  $\alpha$  varies with  $A$ . We used  $A = 40$ , for which the Gribov corrections evaluated in [15] lead to  $\sigma_{eff} \sim 20$  mb. Then a simple expression Eq. (6) explains the observed  $x_F$  scaling and describes rather well the data.

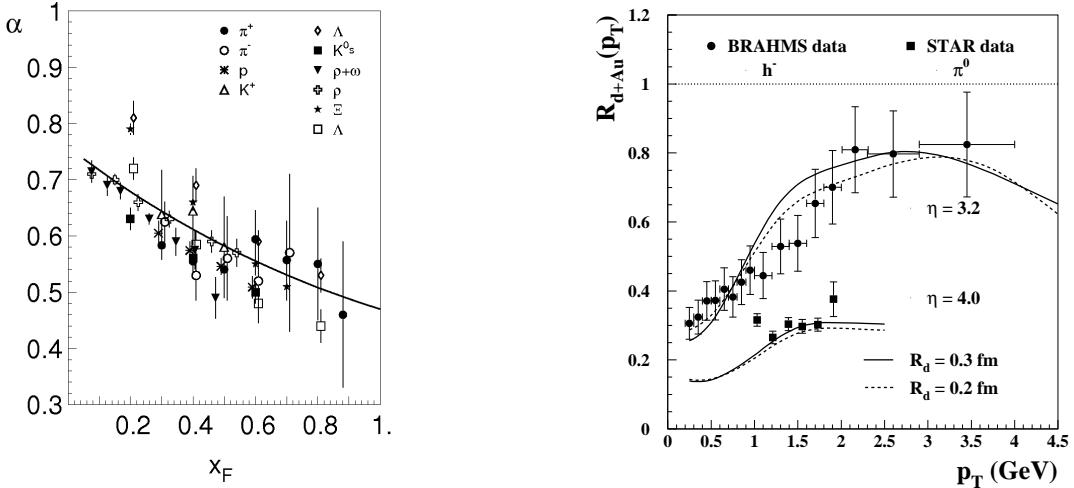
## HIGH- $p_T$ HADRON PRODUCTION AT FORWARD RAPIDITIES

The cross section of hadron production in  $dA(pp)$  collisions is given by a convolution of the distribution function for the projectile valence quark with the quark scattering cross section and the fragmentation function,

$$\frac{d^2 \sigma}{d^2 p_T d\eta} = \sum_q \int_{z_{min}}^1 dz f_{q/d(p)}(x_1, q_T^2) \left. \frac{d^2 \sigma[qA(p)]}{d^2 q_T d\eta} \right|_{\vec{q}_T = \vec{p}_T/z} D_{h/q}(z), \quad (7)$$

where  $x_1 = \frac{q_T}{\sqrt{s}} e^\eta$ . The quark distribution functions in the nucleon have the form using the lowest order parametrization of Gluck, Reya and Vogt [16]. We used proper fragmentation functions using parametrization from [17].

Interaction with a nuclear target does not obey factorization, since the effective projectile quark distribution correlates with the target. The main source of suppression at large  $p_T$  concerns to multiple quark rescatterings in nuclear matter. Summed over multiple



**FIGURE 1.** (Left) Exponent describing the  $A$  dependence ( $\propto A^\alpha$ ) of the nucleus-to-proton ratio for production of different hadrons as a function of  $x_F$ . (Right) Ratio of negative hadron and neutral pion production rates in  $d - Au$  and  $pp$  collisions as function of  $p_T$  at pseudorapidity  $\eta = 3.2$  and  $\eta = 4.0$  vs. data from the BRAHMS [1] and STAR Collaborations [3], respectively.

interactions, the quark distribution in the nucleus reads,

$$f_{q/N}^{(A)}(x_1, q_T^2) = C f_{q/N}(x_1, q_T^2) \frac{\int d^2 b \left[ e^{-x_1 \sigma_{eff} T_A(b)} - e^{-\sigma_{eff} T_A(b)} \right]}{(1-x_1) \int d^2 b \left[ 1 - e^{-\sigma_{eff} T_A(b)} \right]}, \quad (8)$$

where the effective cross section  $\sigma_{eff} = \sigma_{eff}(p_T, s) = \langle \sigma_{\bar{q}q}^2(r_T) \rangle / \langle \sigma_{\bar{q}q}(r_T) \rangle$  has been evaluated in [9]. The normalization factor  $C$  in Eq. (8) is fixed by the Gottfried sum rule.

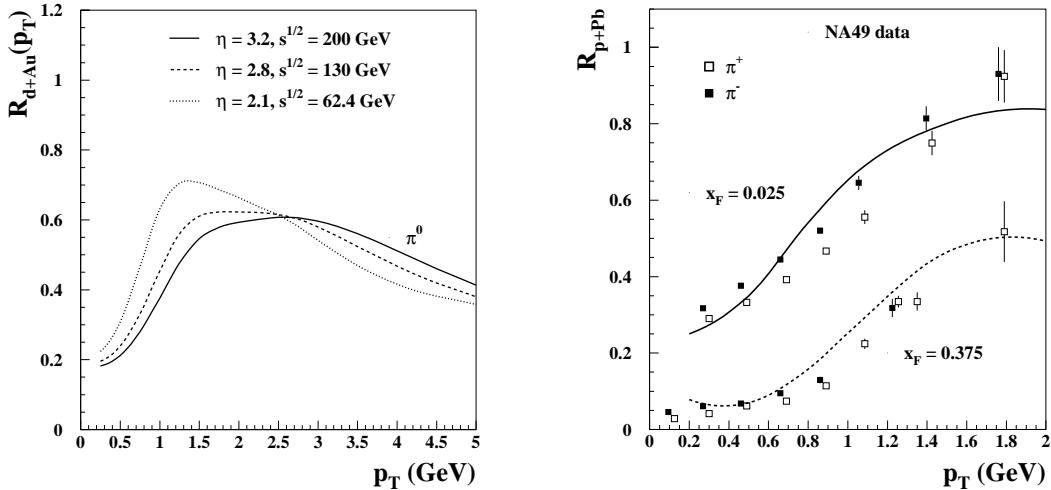
The cross section of quark scattering on the target  $d\sigma[qA(p)]/d^2 q_T d\eta$  in Eq. (6) is calculated in the light-cone dipole approach [18, 19]. In our calculations, we separate the contributions characterized by different initial transverse momenta and sum over different mechanisms of high- $p_T$  production. Details can be found in [9].

The BRAHMS Collaboration [1] in 2004 found a substantial nuclear suppression for high- $p_T$  negative hadrons produced at pseudorapidity  $\eta = 3.2$ . Two years later, the STAR Collaboration [3] has been observed even stronger suppression for neutral pions at  $\eta = 4.0$  as one see from the right panel of Fig. 1. Because the data cover rather small  $x_2 \sim 10^{-3}$ , the interpretation of such a suppression has been tempted to be as a result of saturation [20, 21] or the CGC [22], expected in some models [23].

Even if one supposes to interpret the observed suppression at  $\eta = 3.2$  in terms of CGC, such an interpretation should fail at larger  $\eta = 4.0$ , where the observed suppression is more than a factor of 2 larger. The stronger onset of the quantum coherence effects at  $\eta = 4.0$  can not explain such a huge rise of nuclear suppression.

Much stronger nuclear effects at  $\eta = 4$  can be simply explained by the energy conservation as a much smaller survival probability of LRG at larger  $\eta$ -values [9, 11].

Energy conservation applied for multiple parton rescatterings leads to  $x_F$  scaling of nuclear effects [9, 10, 11]. We expect approximately the same nuclear effects at



**FIGURE 2.** (Left) Theoretical predictions for an approximate  $\exp(\eta)/\sqrt{s}$ - scaling of the ratio  $R_{d+Au}(p_T)$  for  $\pi^0$  production rates in  $d - Au$  and  $pp$  collisions. (Right) Ratio,  $R_{p+Pb}(p_T)$ , for  $\pi^\pm$  production rates in  $p - Pb$  and  $pp$  collisions as function of  $p_T$  at two fixed values of Feynman  $x_F = 0.025$  and  $0.375$  vs. the NA49 data [6].

different energies and pseudorapidities corresponding to the same values of  $x_F$ . Such a situation is demonstrated in the left panel of Fig. 2, where we present  $p_T$  dependence of nuclear attenuation factor  $R_{d+Au}(p_T)$  for  $\pi^0$  production at different c.m.s. energies and  $\eta$  keeping the same value of  $x_F$ .

## NUCLEAR SUPPRESSION AT SMALL ENERGY VS. NA49 DATA

The right panel of Fig. 2 clearly demonstrates a stronger onset of nuclear effects at larger  $x_F$ . The model predictions for nuclear suppression have been performed employing the dipole formalism and using the mechanisms for the valence quarks described in [9]. One can see a good agreement of our calculations with NA49 data [6].

## HIGH- $p_T$ HADRON PRODUCTION AT MIDRAPIDITIES

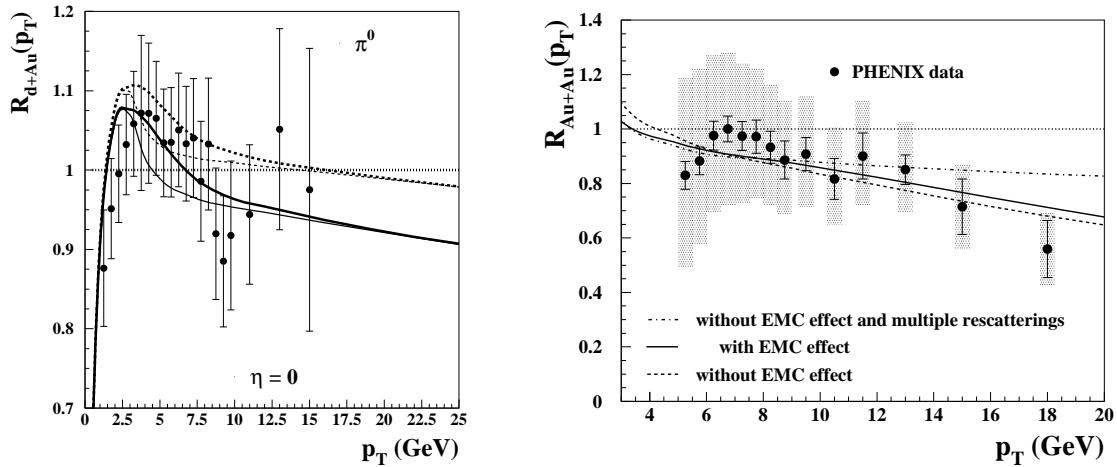
As a consequence of  $x_F$ - scaling is an expectation of similar nuclear effects also at midrapidity. However, the corresponding values of  $p_T$  should be high enough to keep the same value of  $x_F$ . Such an expectation is confirmed by the recent data from the PHENIX Collaboration [4] showing an evidence for nuclear suppression at large  $p_T > 8 \text{ GeV}$  (see the left panel of Fig. 3).

At  $\eta = 0$  the small- $p_T$  region is dominated by production and fragmentation of gluons. On the other hand, the region of very large  $p_T$  is dominated by production and fragmentation of valence quarks. Consequently, any value of the hadron transverse momentum differs only in the relative contributions of valence quarks and gluons.

It means that we include also gluons in our calculations. Details can be found in ref. [24]. Correspondingly, the cross section for hadron production, Eq. (6), is extended also for gluons with corresponding distribution function, parton scattering cross section

and the fragmentation function. Including multiple parton interactions, the gluon distribution in the nucleus is given by the same formula as for quarks (see Eq. (8), except  $\sigma_{eff}$ , which should be higher by the color factor 9/4).

If the effects of multiple parton rescatterings are not taken into account the  $p_T$  dependence of  $R_{d+Au}(p_T)$  is described by the thin dashed line. One can see from the left panel of Fig. 3 that our calculations at moderate  $p_T$  are not in a bad agreement with data and a small suppression at large  $p_T$  is given by the isospin effects. After inclusion of multiple parton rescatterings the model predictions presented by the thin solid line underestimate the data at moderate  $p_T$ . However, at larger  $p_T$  quite a strong onset of nuclear effects is not in disagreement with corresponding experimental points.



**FIGURE 3.** (Left) Nuclear attenuation factor  $R_{d+Au}(p_T)$  as a function of  $p_T$  for production of  $\pi^0$  mesons at  $\sqrt{s} = 200$  GeV and  $\eta = 0$  vs. data from PHENIX Collaboration [4]. (Right) Nuclear modification factor for direct photon production in  $Au - Au$  collisions as a function of  $p_T$ .

Calculations in the RHIC energy range at midrapidities are most complicated since this is the transition region between the regimes of long (small  $p_T$ ) and short (large  $p_T$ ) coherence lengths. Instead of too complicated rigorous light-cone Green function formalism [25, 26, 27, 28] we preset corrections for finite coherence length using the linear interpolation performed by means of the so-called nuclear longitudinal form factor [24]. Such a situation is described by the thick solid and dashed lines reflecting the cases with and without inclusion of the multiple parton rescatterings, respectively. It brings the model predictions to a better agreement with data at moderate  $p_T$ . Nuclear suppression at large  $p_T > 10$  GeV observed by the PHENIX experiment [4] can not be explained as a result of CGC because data cover rather large  $x_2 \sim 0.05 - 0.1$ .

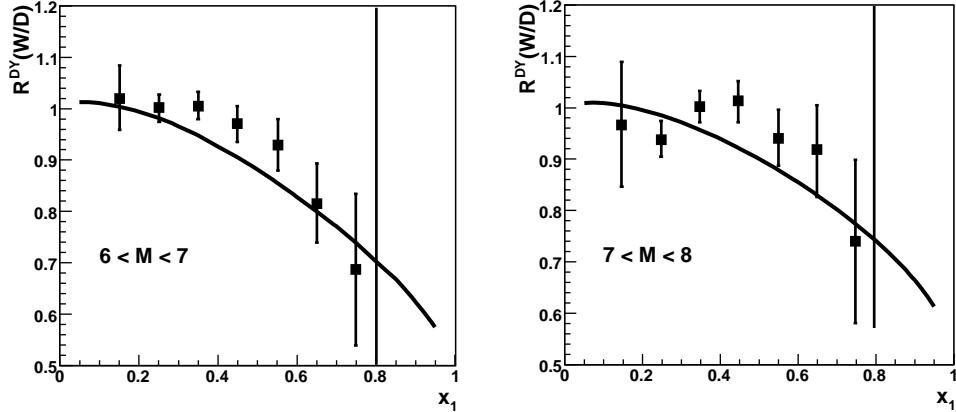
## DIRECT PHOTON PRODUCTION IN AU-AU COLLISIONS

Expressions for the production cross sections have been derived employing the dipole formalism [29, 30, 31, 19, 32]. Model predictions for  $R_{Au-Au}$  as a function of  $p_T$  are compared with the PHENIX data [7] in the right panel of Fig. 3. If multiple parton rescatterings are not taken into account the model calculations depicted by the dash-dotted line overestimate the data at large  $p_T \gtrsim 13$  GeV. The onset of isospin effects gives

a value  $R_{Au-Au} \rightarrow 0.8$  in accord with our calculations. Inclusion of the multiple parton rescatterings leads to a stronger nuclear effects at large  $p_T$  as is demonstrated by the dashed line. It brings a better agreement of the model with data. Finally, the solid line additionally includes also a small correction for the EMC effect [33].

## DRELL-YAN PRODUCTION AT LARGE $x_F$

The DY reaction is also known to be considerably suppressed at large  $x_F$  [34] as one can see from Fig. 4. Model calculations have been performed using expressions for the production cross sections in the color dipole approach [30, 31]. We included also the effect of multiple parton rescatterings [9, 10, 11] discussed above. Model predictions are in a reasonable agreement with data from the E772 experiment [8].



**FIGURE 4.** Ratio of Drell-Yan cross sections on Tungsten and Deuterium as a function of  $x_1$ .

## SUMMARY AND CONCLUSIONS

In this paper we analyze a significant nuclear suppression at forward rapidities (large  $x_F$ ) for several processes. The new results are the following :

- QCD factorization fails at the kinematic limits,  $x_F \rightarrow 1$ ,  $x_1 \rightarrow 1$ . Nuclear targets cause a suppression of partons with  $x \rightarrow 1$ , due to energy sharing problems.
- Suppression of high- $p_T$  hadrons at large rapidity observed by the BRAHMS and STAR Collaborations is well explained.
- We predict  $x_1$  ( $x_F$ ) scaling, i.e. the same nuclear effects at different energies and rapidities corresponding to the same value of  $x_1$  ( $x_F$ ).
- Model predictions are in a good agreement with NA49 data [6] and clearly demonstrate the rise of nuclear suppression with  $x_F$ .
- Predicted strong nuclear suppression for the large- $p_T$  direct photon production in  $Au - Au$  collisions is in a good agreement with the PHENIX data [7].
- According to  $x_F$  scaling we predict nuclear suppression at large  $p_T$  also for hadron production at  $\eta = 0$ . Model calculations describe well the PHENIX data [4].

- Study of nuclear effects at midrapidities is very important because at large  $p_T$  the data cover rather large  $x_2 \sim 0.05 - 0.1$ , where no effect of coherence is possible. It allows to exclude the saturation models or the models based on CGC.
- Suppression of Drell-Yan pairs at large  $x_F$  observed by E772 Collaboration [8] is well explained.

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